Fresh-cut Vegetables

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Introduction: Wounds inflicted during the preparation of fresh-cut vegetables promote many physical and physiological changes that hasten loss of product quality (Brecht, 1995; Saltveit, 1997). Foremost among these, are the removal of the protective epidermal layer and/or exposure of internal cells. These changes not only facilitate water loss, but also provides an easy entry for microbial pathogens and chemical contaminants. Packaging and/or application of edible films can lessen water loss by maintaining a high RH near the cut surface, and providing a physical barrier that protects the product from contamination.

Water loss and collapse of injured cells at the cut surface can alter the appearance of the fresh-cut product. As the cut surface loses water, adhering cellular debris may impart a white blush to the surface that masks varietal color, eg., white blush on 'baby' carrots decreases the intensity of the underlying orange color. Differential dehydration of exposed cortex and vascular tissue may produce an uneven surface, eg., vascular strands projecting a few millimeters from the cut end of celery petioles. Consumers associate both of these surface changes with the loss of freshness.

Physiological processes devoted to wound repair can be beneficial (eg., curing of potatoes) or detrimental to quality retention. Physiological changes following wounding include increased respiration and ethylene production, promotion of the ripening of climacteric fruit vegetables (eg., melons, tomatoes), and enhanced synthesis and accumulation of phenolic compounds that contribute to tissue browning. These changes are managed by the use of low temperatures, creation of reduced O_2 and/or elevated CO_2 atmospheres, and the application of inhibitors of specific chemical reactions or metabolic pathways.

Wound enhanced respiration and ethylene production can deplete carbohydrate storage reserves and stimulate tissue softening associated with fruit ripening (eg., melons, squash, tomatoes) or chlorophyll loss associated with leaf or tissue senescence (eg., spinach, broccoli). In many tissues, wounding produces a signal that induces the increased synthesis and accumulation of phenolic compounds. Tissue browning can result from the oxidation and/or polymerization of accumulated phenolics compounds. Lignification and toughening of tissue are others way in which the metabolism of phenolic compounds can reduce quality.

Sanitation, implementation of Good Agricultural Programs (GAP's) in the field, use of Good Manufacturing Programs (GMP's) and Hazard Analysis and Critical Control Point (HACCP) monitoring plans during all steps of processing, and proper temperature control, are all needed to insure that an initial low microbial load on fresh-cut vegetables is maintained during marketing. The current industry standard washing and disinfection procedures used on whole produce are rather ineffective with fresh-cut vegetables once they have been contaminated with microbial pathogens. Overall microbial load relative to spoilage organisms usually remain below levels of concern as long as visual quality remains acceptable. However, postharvest treatments that maintain visual quality under abusive temperatures may allow microbial loads to reach dangerous levels before quality is reduced below acceptable levels.

Many vegetables are sensitive to non-freezing temperatures below around 50 °F (10 °C), and suffer physiological damage if held at these chilling temperatures beyond a specific period of time. These vegetables include jicama, pepper, sweet potato, tomato and zucchini. In contrast to the whole commodity that should not be chilled, the increased susceptibility of fresh-cut products to spoilage often means that the product has a longer market life at 32 °F (0 °C) than at higher, non-chilling temperatures. Development of chilling injury symptoms is less pronounced in riper tissue, and takes some time to develop. Since most fresh-cut vegetables are consumed soon after purchase and fruit vegetables are fully ripe when processed, chilling injury symptoms usually do not develop to a significant extent because the rate of deterioration due to chilling is slower than the rate of spoilage that is inhibited by low temperatures. The two most important fresh-cut commodities, lettuce and carrots, are not chilling sensitive and should be stored as close to 32 °F (0 °C) as possible without freezing, ie., at 34 to 38 °F (1 to 3 °C) in a commercial setting.

The imposed physical damage done to the product during preparation, and it's increased vulnerability to deleterious internal and external changes, requires that fresh-cut vegetables be handled with a greater degree of care than the whole product. Storage requirements for intact produce may be inadequate to handle increased physiological activity and susceptibility to water loss encountered with fresh-cut vegetables.

The highest quality that is available (usually USDA No. 1) and that is compatible with an economic return should be used for processing. Although poor quality pieces of fresh-cut product can be discarded to upgrade quality (eg., culling discolored pieces of cut lettuce leaves or broccoli florets), the associated cost usually adversely impacts quality and yields, and greatly outweighs the differential cost of using higher quality raw material.

The remainder of this chapter provides information on the commercial packaging and storage of a number of fresh-cut vegetables.

BEETS, Red (grated, cubed, whole peeled)

Fresh-cut beets should be stored at 34 to 38 °F (1 to 3 °C) before and after processing. Respiration is slightly reduced during storage in 5% O_2 + 5% CO_2 at 5 °C (41 °F).

Respiration Rates:

Temperature	Whole Peeled	Cubed (1 x 1 cm)	Grated (2 mm)
		(mg CO_2 kg^{-1} h^{-1})	
2 °C	4	10	12
5 °C	6	12	16
10 °C	19	27	38
23 °C	54	117	162 to 207

To get mL kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU per ton per day or by 61 to get kcal per metric ton per day. Data from Gorny, 1997.

BROCCOLI (Florets)

Fresh-cut broccoli florets should be tight, firm, turgid and dark green without blooming buds. There should be no sulfur odor or discoloration along the stems and cut ends. The core temperature of raw material should be < 1.5 °C (35 °F). Raw and processed material should be stored at 34 to 38 °F (1 to 3 °C) to assure quality and reduce potential for freezing of product during handling, distribution and storage. Yellowing is a common problem caused by either chlorophyll loss or blooming of the buds. The cut surface and damaged floret stems can turn black during storage. Development of off-odors can be a major concern when MAP is used. Temperature abuse promotes soft rot and mold growth.

Whole broccoli heads are hand-cut into florets that are > 1 in (2.5 cm) to < 2 in (5 cm) long. They are washed in water containing up to 200 ppm total chlorine to wash residual material from the florets as well as reduce aerobic plate counts. Repeated daily washing did not maintain lower microbial counts for > 2 days.

The benefit of CA (5% O_2 + 4% CO_2) may be marginal for storage up to 14 days at 32 to 41 °F (0 to 5 °C) compared to air. Lowering O_2 to 0.25% or increasing CO_2 to 10% at 32 to 41 °F (0 to 5 °C) reduces respiration by about 50%. Using appropriate polymeric film in MAP, maintained green color at 32 to 41 °F (0 to 5 °C) for more than 21 days (Cabezas and Richardson, 1997). Severe off-odors and discoloration at cut ends can develop during MAP storage at 10% CO_2 + 2.5% or less O_2 (Makhlouf et al., 1989). Perforated and micro-perforated polymeric packages reduce off-odor formation (Izumi et al., 1996a). Reducing ethylene levels below 1 to 10 µL L^{-1} did not significantly reduce color loss at 34 °F (1 °C), but did have a significant affect at higher temperatures.

No food-borne disease outbreak has been reported associated with fresh-cut broccoli although the aerobe population is usually high (> 100,000 cfu/g fresh weight). Florets stored in 5% O_2 + 8% CO_2 at 46 °F (8 °C) have lower aerobic plate counts, total coliform plate counts, and yeast/mold plate counts compared to storage in air.

Respiration Rates: fresh-cut florets

Temperature	mg CO_2 kg^{-1} h^{-1}
0 °C	26
5 °C	44
10 °C	78

To get mL kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU per ton per day or by 61 to get kcal per metric ton per day. Data from Watada et al. (1996) and Izumi et al. (1996a).

CABBAGE, Green and Red (shredded, diced)

Fresh-cut green cabbage should be light green with a moderate pungent flavor and no sulfur aroma. Raw and processed material should have typical cabbage flavor with no off notes, and should be stored at 34 to 38 °F (1 to 3 °C) to assure quality and reduce potential for freezing of product during handling, distribution and storage. Fresh-cut cabbage includes diced and shredded product with cut size varying from ¼ in (0.63 cm) to 3/8 in (0.95 cm). Heads are trimmed to remove wrapper leaves and cored, cut, and washed using chlorinated water (100 ppm of total chlorine) for about 1 min before being spun-dried and packaged. For coleslaw, cut cabbage (shredded or diced) can be pre-blended with carrots or plain-packaged.

A CA of 5 to 7.5% O_2 + 15% CO_2 is recommended (Hiroaki et al., 1993). Lowering O_2 below 5% caused rapid proliferation of fermentative bacteria and off odors within 6 days at 5°C. The fermentation induction point of coleslaw mixes in low density polyethylene bags varied with the cabbage to carrot ratio, and temperature. At 41 °F (5 °C), a 70:30 mix went anaerobic at 1.8% O_2, while 3% O_2 was the limit for aerobic respiration at 10°C.

Off-odors formation in cut cabbage bags with low OTR film (< 3,000 mL/m^2 atm^{-1} day^{-1}) and discoloration of cabbage leaf packed in high OTR film (> 12,000 mL/m^2 atm^{-1} day^{-1}) bags are the major quality deterioration during storage (Pirovani et al., 1997). At 52 °F (11 °C), *Listeria* spp grew faster in fresh-cut cabbage packages which have an atmosphere of < 1.8% O_2 + > 20% CO_2 than in air (Omary et al., 1993).

Respiration Rates: shredded

Temperature	3/8 in (9.6 mm)	1/4 in (6.4 mm)
	(mg CO_2 kg^{-1} h^{-1})	
2 °C	16 to 18	18 to 24
5 °C	22 to 33	25 to 39
10 °C	42 to 48	51 to 57
23 °C	117 to 153	153 to 171

To get mL kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU per ton per day or by 61 to get kcal per metric ton per day. Data from Watada et al. 1996

CABBAGE, CHINESE (sliced, sticks, shredded)
Fresh-cut Chinese cabbage should be handled like cabbage and stored at 34 to 38 °F (1 to 3 °C). The recommended CA is 5% O_2 + 5% CO_2; benefits are moderate compared to air storage at 32 °F (0 °C).

CARROTS (diced, shredded, sticks, peeled, grated, sliced, cubes)
Fresh-cut carrots are orange without a white brush or slimy surface. Raw and processed product should be kept at 34 to 38 °F (1 to 3 °C) to assure quality and reduce potential for freezing of product during handling, distribution and storage. Most quality loss in cut carrots results from either formation of white blush, or off-odor and slimy surface generated by bacteria (Carlin et al., 1989).

Fresh-cut carrots include whole peeled (baby), sticks, sliced, shredded, grated and diced. Whole carrots are washed with water to remove undesirable field material. The stems and tips are excised and the trimmed carrots are peeled, cut, and washed in 100 µL L^{-1} NaOCl for less than 1 min. Washed carrot cuts are centrifuged to remove excess water and packaged in plastic bags.

Dehydration of surface debris on cut and peeled carrots imparts a whitish translucent appearance to the surface (Tatsumi et al., 1991; Cismeros-Zevallo et al., 1995), which is undesirable because consumers associate it with the loss of freshness (Bolin and Huxsoll, 1991). Application of edible coating (Howard and Dewi, 1995, 1996, Li and Barth, 1998), such as sodium caseinate-stearic acid (Avena-Bustillos et al., 1994) or heating and raising the pH (Bolin and Huxsoll, 1991) may be helpful in reducing white blush. Treatments that modifying the water retaining capacity of the cut surface also prevent white blush development (Cisneros-Zevallos et al., 1997).

Fresh-cut carrots derive slight benefit from 2 to 5% O_2 + 15 to 20% CO_2 atmospheres (Izumi et al., 1996b). Lower O_2 or increased CO_2 levels promoted slimy appearance, increased lactic acid bacteria growth, and accelerated microbial decay and excessive alcohol production. Grated carrots retain good quality for up to 10 days at 36 to 52 °F (2 to 10 °C) in MAP with high O_2 permeability films of 10 to 20 L m^2 atm^{-1} day^{-1} at 25°C (Carlin et al., 1990). Low permeability films of 950 mL m^2 atm^{-1} day^{-1} resulted in low O_2 damage.

The quality and headspace composition of sliced carrots (0.5 cm) treated with 1% ascorbic acid before packing in MAP was unaffected during 14 days at 40 °F (4 °C) (Galetti et al. 1997). Growth of aerobic mesophilic bacteria on sticks was suppressed by a 0.5% O_2 + 10% CO_2 atmosphere at both 32 and 41 °F (0 and 5 °C); but total microbial count on slices and shreds was unaffected.

The mean microbial population after 9 days storage was much lower (1,300 CFU g^{-1}) for irradiated shredded carrots (0.5 kGy) than for non-irradiated, chlorinated controls (87,000 CFU g^{-1}) (Hagenmaier and Baker, 1998). Ethanol and O_2 content of the headspace were not affected.

Respiration Rates:

Temperatures	Whole-peeled	Sliced	Sticks	Shredded
		(mg CO_2 kg^{-1} h^{-1})		
0 °C	---	5	11	15
5 °C	9 to 12	13	19	24
10 °C	17 to 21	25	42	46
23 °C	54	72 to 81	---	108 to 126

To get mL kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU per ton per day or by 61 to get kcal per metric ton per day. Data from Gorny 1997.

CELERY (diced, sliced, sticks)
Fresh-cut celery petioles have no leaves or brown spots, and should not have cracked, flared or white-blush ends. Raw material should arrive at < 38 °F (7 °C) and be stored at 36 to 40 °F (2 to 4 °C) before processing, and at 34 to 38 °F (1 to 3 °C) after processing, to assure quality and reduce potential for freezing of product during handling, distribution and storage. Atmospheres of 5% O_2 + 4% CO_2 were slightly beneficial. Water loss is the main factor affecting eating quality (Gariepy et al., 1986). Small amounts of water loss (2.5 to 5%) can result in litheness, flaccidity, shriveling and wrinkling. Moisture loss can be reduced 75% by the application of an edible coating (Avena-Bustillos et al., 1997). Differential dehydration of exposed cortex and vascular tissue caused the stronger vascular strands to project a few millimeters from the cut end of celery petioles. Development of pithiness is associated with water stress during growth and wounding during processing (Saltveit and Mangrich, 1996). Heat-shock treatments prevented tissue browning without adversely affecting other quality parameters (Loaiza-Velarde et al., 2002).

Sliced celery can only be maintained for 6 days at 40 °F (4.4°C) without notable quality change (Johnson et al., 1974). Major pathogens are *Pseudomonas fluorescens* and *P. Marginalis,* which cause water soaking, soft rot, and discoloration (Robbs et al., 1996). Low-dose irradiation (1.0 kGy) delayed microbial spoilage in fresh, diced celery stored at 40 °F (4 °C) for 3 weeks without affecting sensory attributes. In contrast, blanching and chlorine rinsing had little effect on microbial count. Sensory results indicated the 1 kGy sample was preferred over all other treatments in terms of taste, texture and color.

GARLIC (peeled)
Quality problems with peeled garlic include sprouting and discoloration of areas damaged during peeling. Garlic cloves can be peeled manually or mechanically with compressed air. Acid treatments and edible coatings can improve preservation. Excellent visual quality was maintained for 21, 16, 12 or 8 days of storage in air at 32, 41, 50, or 59 °F (0, 5, 10, or 15 °C), respectively. Decay was not observed at 32 or 41 °F (0 and 5 °C), and was slight at 50 and 59 °F (10 and 15 °C). At 41 and 50 °F (5 and 10 °C), a 1% O_2 + 10% CO_2 CA gave the best quality (lack of decay and least discoloration). Respiration rates in manually peeled garlic were 50% higher than unpeeled cloves. Mechanically-peeled garlic has rates of respiration 5 to 10% higher at 41 °F (5 °C) and 20 to 30% higher at 50 °F (10 °C), than hand-peeled cloves.

Respiration Rate: peeled

Temperature	mg CO_2 kg^{-1} h^{-1}
5 °C	35
10 °C	57

To get mL kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU per ton per day or by 61 to get kcal per metric ton per day. Data from Burlo-Carbonell et al., 2000.

JICAMA (sticks, cubes)
Fresh-cut jicama should be white with a crisp texture. Raw material should be received at < 44 °F (7 °C), and processed product stored at 34 to 38 °F (1 to 3 °C) to assure quality and reduce potential for freezing of product during handling, distribution and storage. Tuber size does not affect visual quality or color. Browning can be a significant cause of quality loss after 9 days at 41 °F (5 °C). Increased storage temperature results in accelerated discoloration. The best treatment to control browning is a 2-min dip in water at 122 °F (50 °C) and then storage at 36 °F (2 °C).

Quality loss during storage at 0 or 5°C in air is also attributable to yeast and bacterial growth. A 10% CO_2 atmosphere retards brown discoloration, maintains crisp texture, and delays microbial growth.

However, acetaldehyde and ethanol concentrations are higher after 8 days at 41 °F (5 °C) in 10% CO_2 atmospheres + 3% O_2 or air. Atmospheres of 20% CO_2 can damage jicama if stored longer than 8 days.

KALE (shredded)
Fresh-cut kale should be dark green, crisp and without yellow or discolored leaf pieces. Raw material should be received at < 45 °F (7 °C) and stored at 34 to 38 °F (1 to 3 °C) after processing to assure quality and reduce potential for freezing of product during handling, distribution and storage. Washing shredded kale with 0.1% NaOCl results in a 10-fold reduction in aerobic plate count compared to unwashed products. Fresh-cut kale in perforated (5.96 ± 0.35 mm^2 diameter holes with 6.68 cm^2 total surface area per sack) polyethylene bags (38 µm thick) become unacceptable due to yellowing and microbial spoilage after 3 days at 39 °F (4 °C). Desiccation, yellowing and spoilage were unacceptable after 1 or 2 days at 68 or 50 °F (20 or 10 °C), respectively (Beaulieu et al., 1997).

LEEK (sliced)
Raw material should be received at, and processed leeks stored at, 34 to 38 °F (1 to 3 °C) to assure quality and reduce potential for freezing of product during handling, distribution and storage. A CA of 5% O_2 + 5% CO_2 is moderately beneficial, and slightly reduces respiration at 41 °F (5 °C). A non-perforated film led to unacceptable material after a few days at 39 °F (4 °C) with high CO_2, ethanol and acetaldehyde concentrations (Keteleer et al., 1993).

Respiration Rates:

Temperature	Whole Leaf	Rings (2 mm thick)
	(mg CO_2 kg^{-1} h^{-1})	
2 °C	24	32
5 °C	29	49
10 °C	38	57 to 67
23°C	117	252 to 288

To get mL kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU per ton per day or by 61 to get kcal per metric ton per day. Data from Gorny, 1997.

LETTUCE, Butterhead, Crisphead, Green leaf, Iceberg, Romaine; (chopped, shredded, whole leaf)
The quality of the fresh-cut product is very dependent on the initial raw product quality. The raw product should be the best quality available, and should be < 36 °F (2 °C) when received as whole or cored heads. It should be stored at 34 to 38 °F (1 to 3 °C) before and after processing to assure quality and reduce potential for freezing of product during handling, distribution and storage.

Browning (enzymatic) of the cut edges is the main defect of fresh-cut lettuce pieces during storage. The best way to prevent the discoloration is to reduce O_2 to < 3%. Antioxidant treatment and heat-shock can inhibit discoloration, but these treatments may result in loss of visual quality. Unless stressed in the field, lettuce has low levels of phenolic compounds and tissue browning occurs after the induction of synthesis and accumulation of phenolics by wounding. A 90 sec heat-shock at 104 °F (45 °C) prevented wound-induced browning of Iceberg (Loaiza-Velarde et al., 1997; Loaiza-Velarde and Saltveit, 2001) and Romaine (Saltveit, 2000) lettuce.

Butterhead lettuce

Browning of the cut edges of butterhead lettuce is reduced by modified atmospheres rapidly created by flushing with N_2 to get 1 to 3% residual O_2, with CO_2 levels of 5 to 10%. Tissue in atmospheres of < 1% O_2 + > 10% CO_2 develop CO_2 injury or brown stain (Stewart and Ceponis, 1968). The incidence of brown stain increased from 16 to 38 to 81% as CO_2 increased from 2.5 to 5 to 10%, respectively, and was enhanced when combined with low O_2 atmospheres (Steward and Uota, 1971).

The physiological behavior of butterhead lettuce, eg., sensitivity to CO_2 injury, is modified by cultural practices such as irrigation, climate and fertilization (Sorensen et al., 1994; Poulsen et al., 1994, 1995). Susceptibility to brown stain varies among cultivars and position of leaves within the head (Krahn, 1977). Shelf-life of butterhead lettuce was negatively correlated with respiration rate and susceptibility to CO_2. High O_2 and low CO_2 enhanced enzymatic browning. Off odors and flavors developed (ethanol, acetaldehyde and ethyl acetate aroma), crispness was lost, and the tissue became translucent when fresh-cut lettuce was stored in < 0.5% O_2 and/or > 15% CO_2.

Necrosis of butterhead lettuce may be associated with microbial growth, such as pectolytic *Pseudomonas* (Nguyen-the and Prunier, 1989) and other epiphytic bacteria.

Respiration Rate: chopped

Temperature	mg CO_2 kg^{-1} h^{-1}
2 °C	12 to 14
4.5 °C	20 to 25
10 °C	38 to 48

To get mL kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU per ton per day or by 61 to get kcal per metric ton per day. Data from Gorny, 1997.

Greenleaf lettuce

A 0.5 to 3% O_2 + 5 to 10% CO_2 CA reduced cut edge browning of green leaf lettuce (Lopez-Galvez et al., 1996).

Iceberg lettuce

The raw product should have < 6% pink rib discoloration, while russet spotting, hooked core and tipburn should be < 1%. Moisture content of lettuce is extremely important for maintaining texture and reducing microbial growth. Excess moisture can be removed in a forced-air tunnel or by spinning. Lettuce that was air dried for 10 to 15 min or spin dried for 30 min had less browning during storage than control samples. Consumer sensory panelists indicated that after 4 days of storage, only 15% would purchase control lettuce while 40% would purchase lettuce spin or air dried for 15 min. Slicing methods can influence ascorbic acid retention in with the order: manual tearing > manual slicing > machine slicing.

In clamshell trays, market-life of fresh-cut lettuce was < 24 h at 73 °F (23 °C), > 24 h at 50 °F (10 °C), and > 48 h at 36 °F (2 °C) (Zhuang and Barth, 1999). Fresh-cut lettuce packages commonly have < 1% O_2 to effectively slow browning and > 10% CO_2 to inhibit microbial growth (Gorny, 1997). An atmosphere of 0.5 to 3% O_2 + 10 to 15% CO_2 reduces cut edge browning, retains visual quality and reduces Psychrophilic bacterial counts. Flushing with 100% N_2 increases retention over MAP. On the basis of ethanol appearance in the headspace, the fermentation induction point was 0.3 to 0.4% O_2 at 41 °F (5 °C) and 0.6 to 0.8% at 50 °F (10 °C). Acetaldehyde and ethyl acetate were detected when O_2 was < 0.4% at 41 to 68 °F (5 to 20 °C). The extent of browning increased with O_2 level, but not with CO_2 level (Smyth-Anne et al., 1998). Fresh-cut Iceberg should be stored at 34 to 38 °F (1 to 3 °C) before and after processing to assure quality and reduce potential for freezing during handling, distribution and storage.

Shelf-life of fresh-cut lettuce at 41 °F (5 °C) was 6 days in air, 8 days in 3% O_2, and 12 days in 0.2% O_2 (Peiser et al., 1997). Increasing CO_2 enhances the beneficial effect of low O_2. A combination of 0.2% O_2 with 7 to 15% CO_2 gave 16 day shelf-life. A 14 day shelf-life was obtained when shredded Iceberg lettuce was stored in 1 to 3% O_2 + 5 to 6% CO_2 at 41 °F (5 °C). However, CO_2 > 15% causes brown stain. Reduced O_2 and/or elevated CO_2 may induce fermentation and off-odor (fermentative volatiles, ethanol and acetaldehyde) formation in the packages (McDonald et al., 1990; Peiser et al., 1997; Mateos et al., 1993).

Although gram-negative bacteria are numerically dominant, a large yeast population may also be found. Species of *Pseudomonas*, *Erwinia*, and *Serratia* were the most frequently isolated bacteria. *Cryptococcus, Pichia, Torulaspora* and *Trichosporon* spp. were the most common yeasts. Beuchat and Brackett (1990) studied the effects of shredding, chlorine treatment and MAP on survival and growth of *Listeria monocytogenes*, mesophilic aerobes, psychrotrophs, yeasts and molds. They found that no significant changes in populations of *L. monocytogenes* were detected during the first 8 days of incubation at 41 °F (5 °C); there was a significant increase between 8 and 15 days. Significant increases occurred within 3 days when lettuce was stored at 50 °F (10 °C). Chlorine treatment, MAP of 3% O_2, and shredding did not influence growth of *L. monocytogenes*.

Respiration Rate: shredded

Temperature	mg CO_2 kg^{-1} h^{-1}
2.5 °C	12.0 to 15.0
5 °C	15.6 to 27.3
7.5 °C	23.1 to 32.7
10 °C	30.4 to 39.9

To get mL kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU per ton per day or by 61 to get kcal per metric ton per day. Data from Gorny, 1997.

Lollo Rosso (Red) lettuce

The beneficial storage atmosphere is 0.5 to 3% O_2 + 5 to 10% CO_2. MAP storage (2 to 3% O_2 + 12 to 14% CO_2) was useful in preventing brown discoloration. However, MAP storage was not beneficial for preserving quality of red tissues and, in fact, their overall visual quality, texture, aroma and macroscopic breakdown under MAP conditions were worse than those of air-stored tissues (Gil-Maria et al., 1998). Castaner et al. (1997) found that after 14 days of storage at 41 °F (5 °C), the overall visual quality of fresh-cut white and green tissue of Loll Rosso (red) lettuce is better in MAP than in air. Green tissue had the lowest overall quality after air storage. In addition, there were no significant overall quality differences for red tissue stored under either condition. Texture and aroma were excellent for green tissue held in MAP, while it was unacceptable in air. Both atmospheres maintained texture of red and white tissues. Aroma was excellent for white tissue in both air and MAP. In contrast, aroma was only acceptable for red tissue stored in air.

Romaine lettuce

Fresh-cut romaine should be stored at 34 to 38 °F (1 to 3 °C) before and after processing to assure quality and reduce potential for freezing of product during handling, distribution and storage. MAP exerted a beneficial effect on sensory quality by preventing pink discoloration. Compared to air, 3% O_2 + 6, 10, or 14% CO_2 MAP delayed development of tissue discoloration and increased shelf-life by about 50%. Of the three CO_2 levels, 10% was slightly more effective than 6 and 14% (Hamsa et al., 1996; Lopez-Galvez et al., 1996; Segall and Scanlon, 1996).

The aerobic plate counts of fresh-cut Romaine lettuce in MAP were decreased by 0.15 and 0.35 kGy gamma irradiation (Prakash et al., 2000). The 0.35 kGy treatment decreased aerobic plate counts by 1.5 logs and yeast/mold counts by 1 log. A combination of MAP and 0.35 kGy resulted in a 2 log reduction in microbial counts. These differences were maintained through 22 days of storage. Irradiation at 0.15 kGy caused smaller reductions in microbial counts. A 10% loss in firmness was observed at 0.35 kGy, while other sensory attributes such as color, generation of off-flavor, and appearance of visual defects were not affected. The control sample reached microbial counts of 10^7 in 14 days compared to the MAP samples that reached the same level in 17 days, and the combination samples (0.35 kGy and MAP) that took 28 days. Color, flavor, and odor were unaffected by irradiation, although an off-odor was obvious in MAP samples after 21 days (17% CO_2 + < 1% O_2). Low-dose irradiation increased shelf-life of cut Romaine lettuce by 2 to 5 days (Guner et al., 1997)

MUSHROOMS (sliced)

Fresh-cut mushroom slices are white with no darkening and wrinkling. Mushroom slices should be stored at 34 to 38 °F (1 to 3 °C). Wrinkling and brown surface patches are due to excessive moisture loss (Roy et al., 1996). A CA of 10% CO_2 + 3% O_2 maintains quality, while 5% O_2 + 5% CO_2 at 5 °C slightly reduces respiration. More than 20% CO_2 accelerates tissue darkening, while < 3% O_2 may result in potential *botulinum* toxin production. Inoculation studies have demonstrated that *C. botulinum* type A will sporulate and produce endotoxin in 0.9 to 2% O_2 after 6 days at 75 to 79 °F (24 to 26 °C) (Sugiyama and Yang, 1975; Sugiyama and Rutledge, 1978). It is not recommended to use low O_2 MAP due to the inherent food safety risk.

Respiration Rates: sliced

Temperature	mg CO_2 kg^{-1} h^{-1}
0 °C	20 to 60
5 °C	39 to 88
10 °C	86 to 124

To get mL kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU per ton per day or by 61 to get kcal per metric ton per day. Data from Gorny (1997).

ONIONS (Diced, slivered, rings, chunks)

Fresh-cut onions should have no discoloration, skin and core. Bulbs should be dry, free of decay, firm and 3 to 4” (7.5 to 10 cm) in diameter. The core of whole onions should be 35 °F (1.5 °C) at receiving, and at 34 to 38 °F (1 to 3 °C) before and after processing to assure quality and reduce potential for freezing of product during handling, distribution and storage. The seed stems and new internal growth should be less than 10%; double centers and translucent scale should be less than 5%.

Whole onions are peeled and trimmed by machine or hand. Washing with chlorinated water can be done before or after processing. Bulbs for onion rings are washed with cold water at 32 °F (0 °C) before processing. However, diced and slivered onions are washed using chlorinated water after processing.

Browning, yellowing and development of translucence are major factors affecting the visual quality of diced onion (Blanchard et al., 1996). Cutting causes important biochemical changes in tissues, including development of sulfur aromatic volatiles. These compounds are produced enzymatically by hydrolysis of alliins (odorless derivatives of amino acids) by alliinase (Schwimmer and Weston, 1961; MacLoed, 1970). Among the volatiles present in the aromatic profile of onion are oxides of disulfide, thiosulfinates and propene disulfide, known bacteriostatics (Davidson et al, 1983). Their action on microorganisms may be due to the inhibition of respiratory enzymes containing thiol groups (Augusti, 1990). Thiopropanal-S-oxide, a lacrimogenous factor, has antifungal properties (Sharmon et la., 1979) and may be involved in development of bitterness and browning of onion puree (Howard et al., 1994).

CA of 2 to 5% O_2 + 10 to 15% CO_2 decreases respiration and microbial proliferation, and retains sucrose and pungency of cut onions. Lowering the O_2 level can be beneficial for visual quality, but has no effect on aroma. Enrichment in CO_2 improves both qualities. Rapid reduction of O_2 in the package reduces discoloration. Browning can be slowed slightly by lowering O_2, and more so by CO_2 enrichment. Langerak (1975) reported that freshly cut onion became brown and unacceptable after cooking when wrapped in perforated film, in comparison with onion wrapped in film that achieved MAP conditions more rapidly. Atmospheres containing 1 to 2% O_2 prevent the loss of pyruvic acid, an indicator of onion flavor intensity, and reduce the rate of respiration of the fresh-cut tissue (Mencarelli et al., 1990).

The inclusion of potassium permanganate as an ethylene scrubber and sulfur volatiles in packages of diced onions improves sensory quality. A storage-life of 10 days is possible for fresh-cut onions packaged in polymeric bags without a gas flush and stored at 36 °F (2.2 °C). Addition of absorbents, potassium permanganate and clay, in packages increased shelf-life up to 18 days at 34 °F (1 °C) (Howard et al., 1994; Toivonen, 1997).

Yeasts and molds were virtually absent on diced onion. When present, their count did not increase beyond 10^2 CFU/g (Garg et al., 1990; Blanchard et al., 1996). Psychrotrophic and mesophilic flora increased throughout storage under all treatments. Their growth in diced onion was slowed under CA as compared to air (Blanchard et al., 1996).

Respiration rates vary significantly depending on how long whole onions were in cold storage prior to processing. CA (5% O_2 + 5% CO_2) at 41 °F (5 °C) reduces respiration rate by 25%.

Respiration Rates:

Temperature	Sliced (2 mm thick rings)	Diced (1 x 1 cm)
	(mg CO_2 kg^{-1} h^{-1})	
2 °C	14.0	12.0
5 °C	23.4	15.6
10 °C	38.0	22.8
23 °C	126 to 131	90 to 99

To get mL kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU per ton per day or by 61 to get kcal per metric ton per day. Data from Gorny 1997.

PEPPER, Bell (Diced, Sliced)

Fresh-cut bell pepper should have no discoloration (darkening) or water soaking. Raw material should be received at < 45 °F (7 °C) and stored at 45 to 50 °F (7 to 10 °C), but stored at 34 to 40 °F (1 and 4 °C) after processing to assure quality and reduce potential for freezing of product during handling, distribution and storage. Defects that reduce overall visual quality includes darkening of the green or red pulp, brown discoloration of the cut surfaces, and decay. Whole peppers should be spray-washed before processing and washed after being cored and cut to reduce microbial population. Alternatively, cut pepper can be washed using a combination of open flume and close flume systems.

Although intact peppers are chilling sensitive, it is necessary to store fresh-cut red and green pepper at 32 to 41 °F (0 to 5 °C) to maintain visual quality (El-Bassuoni and Cantwell, 1994). Visual quality was maintained and few compositional changes occurred during 15 days of storage at 34 °F (1 °C) (Abe et al. 1991; Zhou et al., 1992). Full ripe or red peppers are less chilling sensitive than mature-green fruits of the same cultivar.

The recommended CA is 3% O_2 + 5 to 10% CO_2. Levels of CO_2 > 10% can result in tissue darkening and softening. Shelf-life and sensitivity to CO_2 injury varies significantly among cultivars. Air + 10% CO_2 maintains quality at both 41 and 50 °F (5 and 10 °C). Aroma and texture decrease after 6 days in 10% CO_2, but were maintained in air at 0°C. Storage in high CO_2 at 41 °F (5 °C) and air at 32 °F (0 °C) retard decay development. Atmospheres with 5% CO_2 help maintain quality, but are not as effective as 10% CO_2. Fresh-cut pepper pieces that were ripening or were already fully red ripe had better shelf-life than pieces from mature-green fruit (Lopez-Galvez et al., 1997). They also found that visual quality was best maintained in air or CA at 32 °F (0 °C), with important quality loss observed by day 9 at 41 °F (5 °C) and by day 3 at 50 °F (10 °C). Decay is caused by both fungi (*Alternaria* and *Botrytis* spp.) and soft-rot causing bacteria. Diced tissue was more susceptible to decay than slices (Lopez-Galvez et al., 1997).

Respiration Rates:

Temperature	Sliced (5 cm)	Diced (1 x 1 cm)
	($mg\ CO_2\ kg^{-1}\ h^{-1}$)	
0 °C	2 to 6	2 to 9
5 °C	4 to 7	6 to 12
10 °C	6 to 13	11 to 18

To get mL $kg^{-1}\ h^{-1}$, divide the mg $kg^{-1}\ h^{-1}$ rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg $kg^{-1}\ h^{-1}$ by 220 to get BTU per ton per day or by 61 to get kcal per metric ton per day. Data from Gorny 1997.

POTATO (sticks, diced, sliced, peeled)

Fresh-cut potatoes should be firm and without brown discoloration. Enzymatic browning is a major problem in the discoloration of peeled or fresh-cut potatoes. Hand-peeling and lye-peeling result in good quality, while abrasion-peeling is undesirable for fresh potatoes. Anti-browning dips like 0.5% L-cysteine + 2% citrate, in combination with MAP, are needed to prevent browning of whole peeled potatoes. Pre-treatment with heated ascorbate and citrate solutions, prior to a browning inhibitor dip containing 4% ascorbate, 1% citrate and 1% sodium pyrophosphate, has greatly extended storage-life over that after the dip alone (Sapers and Miller, 1995; Sapers et al., 1997). However, under some conditions, such pre-treatment induced changes in the cooked product that result in surface firming (case hardening) and partial separation of the case-hardened superficial layer from underlying tissue during slicing. Furthermore, case-hardened potatoes form large lumps during mashing (Martin et al., 1999). The recommended storage temperature is 32 °F (0 °C). Shelf-life of minimally-processed products can be extended to 3 weeks under CA and refrigeration.

Dipping potato strips in chlorine solutions (100 and 300 ppm) result in higher microbial populations during storage, while potatoes treated with anti-browning solutions combined with MAP showed only a slight increase. MAP had no significant effect on microbial populations compared to non-packaged samples. The predominant organisms were *Pseudomonas fluorescens* (Gunes et al., 1997).

The recommended CA is 1 to 3% O_2 + 6 to 9% CO_2. Reducing O_2 level to 10 or 3% + 10% CO_2 at 2 °C reduces respiration of potato sticks by 50 to 75%. However, 5% O_2 + 5% CO_2 at 5°C increases respiration of sticks during storage.

Active modification of package atmospheres is necessary to prevent browning and achieve extended shelf-life. MAP alone will not prevent browning (Gurbuz and Lee, 1997). Vacuum packaging of fresh-cut potatoes may create anaerobic conditions that allow growth of *Clostridium botulinum*.

Respiration Rates:

Temperature	Whole Peeled	Halves	Slices (2 mm)	Sticks (0.95 x 0.95 cm)
		($mg\ CO_2\ kg^{-1}\ h^{-1}$)		
2 °C	6.0 to 8.0	8.0	10.0 to 12.0	12.2
5 °C	7.8	7.8 to 9.8	11.7 to 15.6	-
10 °C	17.1 to 19.0	21 to 22.8	38.0	-
23 °C	54 to 63	81	-	117 to 126

To get mL $kg^{-1}\ h^{-1}$, divide the mg $kg^{-1}\ h^{-1}$ rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg $kg^{-1}\ h^{-1}$ by 220 to get BTU per ton per day or by 61 to get kcal per metric ton per day. Data from Gorny (1997).

RUTABAGA (cubed, shredded, peeled)

Fresh-cut rutabaga should have uniform yellow flesh without decay, bruises or discoloration. Raw material should arrive at < 45 °F (7 °C), while raw and fresh-cut product should be stored at 34 to 38 °F (1 to 3 °C) before and after processing to assure quality and reduce potential for freezing during handling, distribution and storage. A CA of 5% CO_2 + 5% O_2 is slightly beneficial and reduces respiration at 41 °F (5 °C).

Respiration Rates:

Temperature	1/4 Whole, Peeled	Shredded (2 mm)	Diced (1 x 1 cm)
		(mg CO_2 kg^{-1} h^{-1})	
2 °C	8	16	18
5 °C	12	20	25
10 °C	15	42	42 to 48
23 °C	45	72 to 81	153 to 162

To get mL kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU per ton per day or by 61 to get kcal per metric ton per day. Data from Gorny (1997).

SPINACH (whole leaves, cut leaves)

Fresh-cut spinach should be green without any decay or bruise. Raw material should arrive at 35 °F (1.5 °C). Fresh and processed products should be stored at 34 to 38 °F (1 to 3 °C) before and after processing to assure quality and reduce potential for freezing of product during handling, distribution and storage.

Storage in 0.8 to 3% O_2 + 8 to 10% CO_2 is beneficial. Spinach stored in 0.8% O_2 at 20°C (68 °F) had a lower respiration rate, superior appearance, and better taste than spinach leaves stored in air (Izumi et al., 1997). Atmospheres of 0.8% O_2 or 0.8% O_2 + 10% CO_2 reduced the number of aerobic mesophilic and psychrotrophic microorganisms on fresh-cut spinach leaves by 10- to 100-fold, compared to air-stored leaves at 41 °F (5 °C); however, there was no effect at 50 °F (10 °C). These atmospheres had no effect on texture changes during storage at 41 °F (5 °C) for 9 days or at 50 °F (10 °C) for 7 days (Babic and Watada, 1996).

An atmosphere of 4% O_2 + 9% CO_2 reduced the loss of ascorbic acid by 50% compared to air (Burgheimer et al., 1967). Increasing CO_2 concentrations up to 13% caused a rapid decrease in ascorbic acid and development of off-odors that were not acceptable after 1 week storage at 45 °F (7 °C) (McGill et al., 1966). Chlorophyll loss can be reduced by 50% with ethylene scrubbing. Low O_2 (0.8%) results in a slightly reduced respiration rate of cleaned spinach leaves.

Microbiological and sensory changes occur in all packaged spinach samples, being more pronounced at 50 °F (10 °C) than at 40 °F (4 °C). Spinach leaves harbor high numbers of mesophilic, psychrotrophic and Pseudomonadaceae bacteria (Babic and Watada, 1996). The pectinolytic species *Pseudomonas fluorescens* is probably the major spoilage agent of fresh-cut spinach. Microbial populations on fresh-cut spinach leaves increase during storage in air and CA at 41 and 50 °F (5 and 10 °C). Populations of Enterobacteriaceae and micrococcaceae are not greatly affected by storage atmosphere.

Respiration Rate: whole leaves

Temperature	mg CO_2 kg^{-1} h^{-1}
0 °C	6.0 to 14.0
5 °C	11.7 to 23.4

To get mL kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU per ton per day or by 61 to get kcal per metric ton per day. Data from Gorny (1997).

SWEET POTATO (shredded, sliced)
Fresh-cut sweet potatoes should be firm and without discoloration. Whole sweet potatoes are washed with water before peeling and shredding. Cut sweet potatoes are then washed with 100 ppm sodium hypochlorite, rinsed, and centrifuged to remove excess water. Product quality remains acceptable during 2 weeks storage at 32 to 40 °F (0 to 4 °C) in polymeric bags. Color of shredded sweet potato darkens and firmness declines during storage. ß-Carotene remains stable at 7.8 mg per 100 g at 40 °F (4 °C). Vitamin C remains stable at 7 mg per 100 g for 1 week and then decreases. A 6.5% CO_2 + 12% O_2 atmosphere is slightly beneficial.

TOMATO (Sliced, Diced)
Fresh-cut tomatoes should have consistent red color and firm texture. Sliced tomatoes have no gel loss from the seed cavities. Diced tomatoes have no seeds and stem pieces. 'Roma' tomatoes are often used for diced tomatoes; the ripening stage should be 5 or higher (USDA standard). The ripening stage of round tomatoes for slicing should be 5.5 or higher. Fruit should be firm and have small seed cavities. For diced tomato products, 'Roma' tomatoes should be spray-washed with chlorinated water before cutting. After cutting, an open fluming system with 0.25% $CaCl_2$ and 100 ppm chlorine is used to wash and remove seeds. For sliced tomato products, whole tomatoes are dipped in 200 ppm chlorinated water for more than 1 min before slicing. Various automated slicing machines have been developed for tomatoes. Sliced tomatoes can be packed with stacking, shingling or soldier style.

Although tomatoes are chilling sensitive, they can be stored at 32 to 41 °F (0 to 5 °C) for a few days before processing to retard softening. A CA of 3% O_2 + 3% CO_2 will delay ripening, as well as SSC and TA losses (Mencarelli and Saltveit, 1988). Water soaking that produces translucent tissue, textural changes, and softening reduces the quality of diced tomatoes during storage. In addition to these deleterious changes, quality of tomato slices can be reduced by seed germination and loss of locular gel. The high acidity of tomato products suppresses microbial growth, but growth of yeasts and molds can reduce quality in storage.

Respiration Rate:

Temperature	mg CO_2 kg^{-1} h^{-1}
20 °C	57.6 to 93.6

To get mL kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU per ton per day or by 61 to get kcal per metric ton per day.

ZUCCHINI (Slices)
Fresh-cut zucchini should have a dark green peel, white tissue and a crisp texture. Raw material should be received at < 55 °F (13 °C) and stored at 41 to 50 °F (5 to 10 °C). Storage should be at 32 to 41 °F (0 to 5 °C) after processing. A CA of 0.25 to 1% O_2 is beneficial. Lowering O_2 to < 0.5% at 41 °F (5 °C) reduces respiration by 50%; respiration is reduced by 80% at 50 °F (10 °C). Sliced zucchini develops water soaked areas (chilling injury) at 32 °F (0 °C) and brown discoloration at 41 to 50 °F (5 to 10 °C) which increases with storage duration. Zucchini slices can be dipped in solutions of $CaCl_2$ alone or with

NaOCl. Calcium treatments reduce development of decay and total microbial growth, and ascorbate loss.

Respiration Rates:

Temperature	mg CO_2 kg^{-1} h^{-1}
5 °C	21.1
10 °C	19.4 to 49.4

To get mL kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU per ton per day or by 61 to get kcal per metric ton per day. Data from Gorny (1997).

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